The Sixth International Workshop on Unstructured Mesh Numerical Modelling of Coastal, Shelf & Ocean Flows

19-21 September 2007

Imperial College London

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Organising Committee

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Dr Matthew Piggott, Imperial College London
Dr Peter Allison, Imperial College London

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Professor David Marshall, University of Oxford
Dr Julie Pietrzak, Delft University of Technology
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Professor Eric Deleersnijder, Université catholique de Louvain
Professor Mohamed Iskandarani, University of Miami
Dr Florent Lyard, LEGOS

Wednesday 19 September

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1025	A finite element stabilization method for advection-diffusion, non-hydrostatic flow and the shallow water equations. *Labeur and Wells*
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1145	RT0 vs P1nc-P1 *Hanert*
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1530	Global Unstructured Grid Ocean Modeling *Stuhne and Peltier*
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0935	Development of prototype datastructure and flow code facilitating future integration of Sobek-1D2D and Delft3D-FLOW *Kernkamp*
1000	Comparison of iterative method for the solution of elliptic equations in ocean models *Iskandarani*
1025	Use of unstructured grids in nearshore wind wave model SWAN *Zijlema*
1050	**Break**
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1120	The inverse finite-element ocean circulation model (IFEOM) and its sensitivity to control parameters *Sidorenko et al.*
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Posters

A comparison of finite difference and finite element approaches for tidal modelling *Androsov and Massmann*

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Stabilisation of subgrid scale information in transport processes *Candy et al.*

LBB Stability of a Mixed Discontinuous/Continuous Galerkin Finite Element Pair *Cotter et al.*

Finite–element ice model and performance of EVP rheology on unstructured grids *Danilov*

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Quadratic fitting for Hessian recovery and anisotropic mesh optimisation *Farrell et al.*

The efficient solution of large aspect ratio pressure Poisson problems using algebraic multigrid techniques *Kramer et al.*

Finite-element model of the Great Barrier Reef circulation *Lambrechts et al.*

Internal wave simulation with ICOM *Martin et al.*

Aspects of spatial discretization on unstructured staggered grids *Wenneker*

On The Scaling Properties of Tetrahedral Supermeshes *West*

Multimaterial modelling on unstructured meshes *Wilson et al.*

A comparison of finite difference and finite element approaches for tidal modelling

Alexey Androsov and Silvia Massmann

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Abstract

Based on the viscous shallow-water equations two model approaches one with a finite difference and the other with a finite element representation are contrasted in order to determine their efficiency, accuracy and robustness. The finite element model was created in two versions: one using explicit velocity and elevation and the other using semi-implicit Coriolis and pressure gradient terms and a semi implicit velocity scheme in the continuity equation. The pros and cons of finite differences on curvilinear coordinates and the different finite element models on unstructured triangular meshes are compared by calculating the solution characteristics of the boundary-value problem. Both schemes are applied to model the tidal dynamics of the Red Sea. Results of M_2 and K_2 waves and their residual currents and a comparative analysis of efficiency are presented.

Automatic mesh generation, mesh smoothing and adaptivity in tsunami propagation applications

Jörn Behrens and Oliver Kunst

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Abstract

In order to generate meshes for complex realistic domains like oceans or lakes, automatic meshing tools are still scarce. We propose to use an adaptive mesh refinement strategy in order to generate meshes of highly complex boundary geometries. This strategy is based on three steps: start with a coarse rectangular grid which overlays the whole domain; refine along the boundaries; when refined cut out those elements, which are positioned outside of the domain. While this strategy is simple, it is not satisfying when applied unmodified. Additional steps make this strategy truly powerful: Firstly, after local refinement, nodes near the boundary are moved onto the boundary. Secondly, mesh smoothing is applied in order to maintain suitable mesh quality even after node movement. Finally, using this automatically generated grid, and applying an adaptive mesh refinement strategy, tsunami wave propagation can be simulated efficiently.

Simulation of tidal flows around a shallow water island with the discontinuous Galerkin method

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Université catholique de Louvain, Belgium

Abstract

The purpose of the present work is the development of an ocean model based on a high order discontinuous finite element discretization. We present some preliminary results concerning the application of the discontinuous Galerkin (DG) method for the resolution of realistic problems of tidal flows around a shallow water island, the Rattray island, located in the Great Barrier Reef.

Realistic elements of the simulation are a tidal flow forcing, a variable bathymetry and a non trivial coastline. The Rattray island has been widely under study in the literature providing useful in situ measurements for validation of the model.

We observe that the high order DG method applied to shallow water flows around bluff bodies with poor linear boundary representations produces oscillations and spurious eddies. Even though those eddies may have the right size and intensity, this is not obviously for the good reasons. Though not interested in solving accurately the boundary layers of an island, we show that a high order boundary representation is mandatory to avoid non physical eddies. It is then possible parameterize accurately the subgrid scale processes to introduce the correct amount of diffusion in the model. The DG results around the Rattray island are then compared to currents measurements.

Open ocean deep convection in ICOM; Characteristic scalings and adaptive mesh results

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Abstract

Jones and Marshall (1993) is a seminal paper in the physics and scaling of open ocean deep convection. They describe how the characteristic scalings rely on rotation rate, and buoyancy forcing, and simulate convective mixing on a fine fixed mesh.

ICOM is an unstructured adaptive mesh ocean model, which has the potential to capture the small scale structures and the large-scale processes simultaneously. The model is described in more detail by Ford et al (2004) and has already been tested and validated against a fixed mesh for the convection test problem.

We will recreate the experiments performed by Jones and Marshall, using ICOM. The effect of varying the rotation rate, and the strength of the forcing will be investigated, as well as the performance of the adaptive mesh.

Stabilization of subgrid scale information in transport processes

Adam S. Candy, Christopher C. Pain and Matthew D. Piggott

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Imperial College London, United Kingdom

Abstract

A consideration of stabilization techniques is essential in ocean model development if finite element-based models are to correctly model ocean processes over a wide-range of scales. Careful application of these techniques can significantly increase flexibility of models and allow meshes to become highly anisotropic. This enables the model to capture a wider range of ocean phenomena and thus reduce the number of parameterizations required, resulting in a more physically realistic solution.

The next generation of ocean models employ unstructured meshes and anisotropic adaptivity to gain a greater degree of flexibility. These however, introduce erroneous artefacts into the solution when, for example, a process becomes unresolvable due to an adaptive mesh change or advection into a coarser resolution of mesh in the domain. The suppression of these effects, caused by spatial and temporal variations in mesh size, is one of the key roles stabilization can play.

Stabilization techniques suitable for application in ocean modelling are discussed, with a focus on consistent and residual-based methods. A newly-developed higher-order scheme is introduced and applied both directly in an implicit Petrov-Galerkin formulation and also in an explicit large eddy simulation model. Results from an application of these are compared alongside established schemes, such as Petrov-Galerkin and Galerkin least-squares, and more recently developed methods derived from subgrid scale modelling concepts for transport processes. A range of problems are considered, including flow over a backward-facing step, a density-driven gravity current and an idealised Stommel gyre.

In combination with adaptive methods, stabilizing techniques are key to the development of next generation ocean models. In particular, these ideas are critical if we are to achieve our aim of extending models, such as the Imperial College Ocean Model, to the global scale.

How to stabilize P1NC-P1 element for unsteady waves simulation ?

Richard Comblen, Eric Deleersnijder, Jean-François Remacle and Vincent Legat

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Université catholique de Louvain, Belgium

Abstract

Finite Element methods are highly compelling for numerical ocean modeling. On one hand, complex topographic features can faithfully be represented by locally increasing the mesh resolution and because there is no constraint on the mesh topology. On the other hand, the systematic use of local coordinates allows to avoid the classical singularity problem occurring at both poles with structured meshes. Our ocean model uses an efficient mixed finite element pair P1NC-P1 for the primitive shallow-water equations that did not support spurious oscillations (Hanert 2005). This pair is a good compromise between continuous and discontinuous Galerkin methods, and appears to behave rather well for shallow water flows. Moreover, the model consistently conserves mass and tracers (White 2007), as we show in the previous workshop.

In this talk, we firstly address the issue to solve problems on the sphere (and even on any curved geometries, in a more general sense). Any global coordinates system cannot be used, since it introduces poles and will generate singularity for the representation of all fields at poles. In a second part, we also adress the issue to efficiently and accurately the element pair P1NC-P1 where the compromise between continous and discontinous Galerkin methods does not allow to introduce a straighforward application of the usual approach used in DG methods. However, it is possible to use the same ideas to build an efficient method.

We present some validation results with the benchmark test cases described by Williamson et al. (1992). It consists on idealized, but quite realistic non-viscous flows on the sphere. We are able to circumvent the singularity problems inherent to global coordinate systems typically encountered. We also demonstrate that accurate and stable results can be obtained with the stabilized version of the method. This new formulation appears to be quite more robust, stable and accurate than the previous implementations of the mixed finite element pair P1NC-P1.

[1] White L, V. Legat and E. Deleersnijder, Tracer Conservation in a Three-Dimensional, Finite Element, Free-Surface, Marine Model on Moving Unstructured Meshes, submitted to Monthly Weather Review (2007).

[2] Hanert E., D.Y. Le Roux D.Y., V. Legat and E. Deleersnijder, An Efficient Eulerian Finite Element Method for the Shallow Water Equations, Ocean Modelling, 10, 115-136 (2005).

[3] Williamson D.L., J.B. Drake, J.J. Hack, R. Jakob, and P.N. Swarztrauber, A Standard Test Set for Numerical Approximations to the Shallow Water Equations in Spherical Geometry, Journal of Computational Physics, 102, 211-224 (1992).

LBB stability of a mixed discontinuous/continuous Galerkin finite element pair

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Abstract

We introduce a new mixed discontinuous/continuous Galerkin finite element for solving the 2- and 3-dimensional wave equations and equations of incompressible flow. The element, which we refer to as $P1_{DG}$-P2, uses discontinuous piecewise linear functions for velocity and continuous piecewise quadratic functions for pressure. The aim of introducing the mixed formulation is to produce a new flexible element choice for triangular and tetrahedral meshes which satisfies the LBB stability condition and hence has no spurious zero-energy modes. We illustrate this property with numerical integrations of the wave equation in two dimensions, an analysis of the resultant discrete Laplace operator in two and three dimensions, and a normal mode analysis of the semi-discrete wave equation in one dimension.

Finite–element ice model and performance of EVP rheology on unstructured grids

S. Danilov

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Abstract

Standard EVP rheology implementation suggests to limit viscosities to keep CFL-type stability. On unstructured grids such limiting is leading to artifacts caused by variable resolution. This implies that a careful choice of EVP subcycling step is generally required in order to minimize the effects of limiting. We briefly present implementation of finite-element ice model of AWI and show how its results are modified by limiting on meshes with variable resolution. We also discuss the influence of advection schemes on the ice model performance.

Direct and inverse POD model reduction applied to a 3-D adaptive Ocean model (ICOM)

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Abstract

A novel Proper Orthogonal Decomposition (POD) model has been developed for use with an advanced unstructured mesh finite element ocean model, the Imperial College Ocean Model, which includes many recent developments in ocean modelling and numerical analysis. The mesh adaptive refinement is first introduced into the POD reduced model. An adaptive POD procedure is employed to improve the reduced model by updating the POD basis. The utility of the new POD reduced order forward and adjoint models is assessed and validated in 2D/3D, time-dependent test cases; - flow past a cylinder, flow past a cylinder and a gyre. The Coriolis effect on the flow is considered in the above cases. The reduced order adjoint model is used to optimise the initial conditions in the gyre case. The new POD model has been validated by comparing 4D-VAR simulation results from adaptive and static meshes. Furthermore the error estimation (including the error in POD reduced modelling and the interpolation error in adaptive meshes) is carried out allowing us to assess the quality of reduced adaptive mesh models.

The POD inverse model developed here has the following abilities: To use dynamically adaptive meshes in the above POD model and inverse problems. To be able to obtain the same length of POD snapshots at each time level, a reference fixed mesh is chosen for the POD reduced model. The results from the full model are interpolated from the adaptive mesh onto the reference mesh for each of the snapshots and stored to find the optimal POD bases;

To increase accuracy when representing geostrophic balance (the balance between the Coriolis terms and the pressure gradient). This is achieved through the use of two sets of geostrophic basis functions where each one is calculated by basis functions for velocities u and v;

To speed up the POD simulation. To achieve this a new numerical technique is introduced, whereby a time-dependent matrix in the discretised equation is

rapidly constructed from a series of time independent matrices. This development imparts considerable efficiency gains over the often used alternative of calculating each finite element over the computational domain at each time level;

To update the POD basis. The original reduced basis for inverse problems is calculated by a set of snapshots based on the results from the full forward model with the specified control variables. The optimised control variables via optimisation techniques could be significantly different from the original ones. An updated reduced basis is therefore needed when the optimisation procedure loses its control based on an error criterion defined in a cost function (or Trust-Region POD approach).

Automated continuous validation for the Imperial College Ocean Model

Patrick E. Farrell

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Abstract

Ocean models are by their nature complex, and rigorous validation on well-understood problems is necessary to give confidence in their applicability to oceanography. We take the view that a continuous approach to validation is required as the code changes; therefore, the model validation must be automated. In this poster the approach to validation of the Imperial College Ocean Model (ICOM) is described. When a change is committed to the code repository, it is automatically compiled on multiple platforms with multiple compilers. If the compile succeeds, the ICOM validation suite is automatically executed, which tests the ocean model on a wide range of simulations, including parallel simulations, to verify the correctness of the new version. If a failure is detected the developers are automatically notified. Such automated tests also allow for the collection of important statistical data about the behaviour of the ocean model, including profiling data regarding the time taken for a given simulation. We conclude that a modern approach to software engineering yields dramatic improvements in code quality and programmer efficiency.

Quadratic fitting for Hessian recovery and anisotropic mesh optimisation

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Abstract

In adaptive mesh modelling, anisotropic meshes which reflect the complexity of the simulation are important for optimising accuracy for a given computational cost. In the context of mesh optimisation methods, the required element sizes and orientations are often specified in terms of a metric tensor field. The metric tensor field is typically computed from a discrete approximation to the Hessian of one or more solution fields. Recently, Vallet et al. compared several Hessian recovery methods and recommended the quadratic fitting algorithm. Here the quadratic fitting algorithm is evaluated in the context of mesh optimisation methods and some problems with implementation and accuracy are discussed. Quadratic fitting is found to be unsuitable in this context and other methods are recommended.

A High-Order Triangular Discontinuous Galerkin Shallow Water Model using Explicit and Semi-Implicit Time-Integrators

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Abstract

This talk describes the high-order triangular discontinuous Galerkin (DG) method that we have developed that uses Lagrange polynomials sampled at the Fekete points for interpolation and at Gauss points for integration. The nodal (Cardinal) basis functions are constructed using the inverse of the modal Proriol-Koornwinder-Dubiner (PKD) functions. This approach naturally gives rise to a full mass matrix which we then eliminate by premultiplying into the weighting functions. To march the equations forward in time we use strongly stability preserving (SSP) explicit methods such as RK3 and BDF2 and, in addition, show how to construct semi-implicit time-integrators in order to be able to use much larger time-steps. We will show results for a variety of oceanic shallow water tests using unstructured adaptive grids including: Rossby soliton and Kelvin waves, the Stommel and Munk problems, and the dam-break (Riemann) problem. These results show that the high-order DG method achieves spectral convergence for smooth flows, and that the semi-implicit time-integrators permit extremely large time-steps to be used. Issues still requiring further work will be introduced and, hopefully, these topics can be discussed at the workshop.

The 3D unstructured model T-UGOm: Development status and validations

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Abstract

The Toulouse Unstructured Grid Ocean model T-UGOm has been under development since late 2005.It is planned to be a very flexible 2D/3D model with flexible options and multiple configurations selectable at runtime. We present here the design targets for the model and the present status of coding and testing.

RT0 vs P1nc-P1

Emmanuel Hanert

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Abstract

The RT0 and P1nc-P1 finite element schemes are among the most promising low order elements for 2D unstructured mesh ocean models. Both elements are free of spurious computational modes and accurately represent inertia-gravity, Rossby and Kelvin waves. Both finite element schemes are compared in terms of formal accuracy, dispersion properties (amplitude and phase shift) and conservation properties. The effect of mass lumping is also investigated and we show that both scheme preserve their good dispersion properties when they are lumped. Finally, we mention some of the issues associated with the discretization of the Coriolis force and show that the finite element formulation naturally leads to a well-behaved Coriolis operator for both elements.

Tsunami Simulations with unstructured grids (TsunAWI) and a comparison to simulations with nested grids (TUNAMI-N3)

Sven Harig

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Abstract

In support of a Tsunami Early Warning System for the Indian Ocea a Finite Element Model (TsunAWI) for simulations of the wave propagation has been developed. It is part of the German Indonesian Tsunami Early Warning System (GITEWS). Model results will be the main source for the prediction of arrival times and expected wave heights. The unstructured grid has a relatively low resolution in the ocean interior (about 10 km) coastal regions however are very well resolved (up to 80 m). This allows to capture both the wave propagation in the deep ocean and inundation processes in the same model without the need of nesting different grids. Numerical experiments simulating the Tsunami in the Indian Ocean generated by the earthquake of Dec. 26 in 2004 have been conducted. The role of the model bathymetry and topography (based on the GEBCO dataset as well as data from the SRTM satellite mission and ship cruises) has been investigated. The inundation obtained in the simulations were compared to field measurements as well as satellite images of Banda Aceh region. Furthermore the results were compared to simulations of the same event by the finite difference model TUNAMI-N3 with three nested grids and resolutions ranging from 900 m in the coarsest grid to 90 m in the finest nested grid. It turned out that the two models coincide fairly well with respect to wave propagation and inundation however a good representation of the near shore bathymetry is crucial for realistic results.

Comparison of iterative method for the solution of elliptic equations in ocean models

Mohamed Iskandarani

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Co-Amplitude, Phase: Tidal Analysis Incorporating Nearshore; Practical Unstructured Grids When Assessing Shelf Hydrodynamics.

J. Eric Jones, Philip Hall and Alan M. Davies

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Abstract

Although there has been significant progress in modelling tides in a large number of geographical areas in recent years, the main focus of this work has been outside the very nearshore coastal domain where "wetting and drying" can occur during the tidal cycle. The main reason for this has been the coarse grid nature of these models which prevented them from resolving these shallow regions. For example shelf wide models of the European continental shelf used a grid resolution of 1/12° and hence could not resolve coastal regions where "wetting and drying" occurred and higher harmonics were generated by non-linear effects. To examine the nearshore generation of higher harmonics, higher resolution limited area finite difference models were developed. The difficulty of using such limited area models to examine the influence of "wetting and drying" in nearshore regions upon the higher harmonics was that because of the limited extent of the model these harmonics were significant at the open boundary of the model. Consequently these harmonics had to be included as open boundary forcing to the model and hence their distribution over the region was not only influenced by nearshore dynamics but also by open boundary forcing. Consequently the effect of nearshore dynamics could not be examined in detail.

An alternative approach to using a uniform finite difference grid is to apply an unstructured finite element approach. Recently a finite element tidal model of the west coast of Britain has been developed based upon the application of the TELEMAC code to solve the finite element equations that describe tidal motion in the region. The finite element grid of this model is ideal for examining the effects of nearshore dynamics upon higher harmonics of the tide for a number of reasons. The most important of these is that the model's open boundary is well removed from the shallow water region, namely the eastern Irish Sea where higher harmonics are important. Also, there is a comprehensive tidal data set, including the higher harmonics for model validation and an accurate solution from a limited area high resolution (1 km) model of the region, for comparison purposes. The objective of this paper is to examine to what extent a range of finite element codes,

namely TELEMAC, ADCIRC and QUODDY can reproduce the higher harmonics of the M_2 tide in the eastern Irish Sea, and the sensitivity of the solution to changes in nearshore water depth. In addition small scale variations of the tide in the near coastal region are used to examine the sensitivity of the solution to grid resolution.

Development of prototype datastructure and flow code facilitating future integration of Sobek-1D2D and Delft3D-FLOW

Herman Kernkamp

WL — Delft Hydraulics, The Netherlands

Coriolis and circumcenter based C-grid unstructured grid models

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Delft University of Technology, The Netherlands

Abstract

The spatial discretisation of a system should be chosen in such a way that the non-growth property of the underlying partial differential equations is maintained. For a circumcenter based unstructured C-grid, we can derive a Coriolis discretisation in such a way that the skew-symmetry of the semi-discrete system is preserved. This will result in stability and energy conservation of a linear system. However if we consider a non-linear system of equations, a time integration method proved to be stable in the linear case, may become unstable since the propagation matrices vary in time. In this case one may set up the space and time discretised system and at each time step analyse the eigenvalues of the time dependent propagation matrix. Some examples using Kelvin wave propagation in a circular basin of constant depth are presented.

The efficient solution of large aspect ratio pressure Poisson problems using algebraic multigrid techniques

Stephan C. Kramer, Christopher C. Pain and Matthew D. Piggott

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Imperial College London, United Kingdom

Abstract

One of the most challenging aspects of global ocean modelling is the great variety of length scales that play a role; small scale features may have a significant impact on the global circulation. The required variability in grid resolution is made possible in unstructured grid models. The presence of various scales however has a seriously negative impact on the conditioning of the discretised system of equations, and thus on the model efficiency.

Already in structured ocean models, the large difference between horizontal and vertical length scales poses a similar problem, especially for those that take non-hydrostatic effects into account. Here the solution of a 3D pressure Poisson equation with a very large aspect ratio is a real challenge. In Marshall et al. (J. Geophys. Res. 102, 1997), an efficient solution strategy is provided that performs well across a whole range of scales, and is able to compete with the performance of shallow water models in the hydrostatic limit.

We will demonstrate how this approach can be generalised for application in unstructured mesh models using algebraic multigrid techniques. The integration of the equation over vertical columns in the approach of Marshall naturally becomes a coarsening step in a more general multigrid framework. This allows for a smooth transition between the near hydrostatic regime and the non-hydrostatic regime where the separation of horizontal and vertical length scales is less prominent. We will show a number of test cases, based on realistic ocean problems, where the application of this approach significantly improves the convergence of the pressure solver.

A finite element stabilization method for advection-diffusion, non-hydrostatic flow and the shallow water equations.

Robert Jan Labeur and Garth N. Wells

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Abstract

A stabilized finite element method is presented which inherits features of both discontinuous and continuous Galerkin finite element methods. A field is defined on interior element boundaries connecting functions on elements that are discontinuous between elements. The approach allows the incorporation of natural upwinding at element boundaries, which is typical of discontinuous Galerkin methods, with the same number of global degrees of freedom as for a continuous Galerkin method. The element matrices to be computed before assembly are very similar to those for the continuous Galerkin method. For linear elements, only minor modifications are therefore required to existing continuous finite element codes.

The method is developed for the advection-diffusion problem, non-hydrostatic incompressible flows with a free surface and the shallow water equations. The talk will elaborate on the link to other stabilized methods and present a range of numerical examples, with particular emphasis on coastal and estuarine applications. These examples confirm that the method is optimally stable with only minimal numerical dissipation.

Finite-element model of the Great Barrier Reef circulation.

Jonathan Lambrechts [a], Vincent Legat [a], Emmanuel Hanert [b] and Eric Wolanski [c]

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[b]*Department of Meteorology The University of Reading, United Kingdom*

[c]*Australian Institute of Marine Science, Australia*

Abstract

An unstructured-mesh, finite element, depth-integrated model of the hydrodynamics of the whole Great Barrier Barrier Reef (GBR), Australia, has been developed and implemented on a parallel computer. Far away from reefs, islands and important bathymetric features, the mesh size may be as large as a few kilometres, whereas, in the vicinity of reefs and islands, the grid is drastically refined, leading to meshes that can be 100 metres in size. This enables our model to simulate motions characterized by a wide range of space and time scales. Large scale currents, i.e. the tides, the wind-induced circulation and the bifurcation of the East Australian Current, are reproduced with an accuracy that is comparable to that achieved by today's large-scale models of the GBR. The model is also successful at representing small-scale processes, such as tidal jets, their instabilities, as well as the eddies developing in the wake of islands and headlands. Both large and small scales have been validated.

Multiscale mesh generation on the sphere

Jonathan Lambrechts [a], Richard Comblen [a],
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Abstract

A method for generating computational meshes for applications in ocean modelling is presented. The method make use of a standard engineering approach for describing the geometry of the domain that requires meshing. The underlying sphere is parametrized unsing stereographic coordinates. Then, coastlines are described using cubic splines that are drawn in the stereographic parametric space. The mesh generation algorithm builds the mesh in the parametric plane using a technique that is described in the paper. The method enables to build coastlines from different data sets, allowing to build meshes of domains with highly variable length scales. The results that are presented include meshes of the world ocean together with a very fine discretization of french Polynesia.

Hydrodynamic modelling of the Amazon estuary and shelf: preliminary results

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Abstract

The French AMANDES project (AMazon ANDEanS), started in 2005, aims to study the exchanges between the continent and the ocean throughout the Amazon river system. In this project, T-UGOm is used to model the river and ocean dynamic with the ultimate objective of precisely describing the Amazone river plume and its associated sediment transport.

From the modeling point of view, the Amazon shelf presents many difficulties: in this region, tidal amplitude is quite strong. On the other hand, the shelf is very shallow. Last but not least, the river current is so strong that it carry a very huge quantity of material. Consequently, the nature of river and ocean bottoms can be very different from one area to others. As a result, the system is very sensible to bottom stress, and the rugosity geographically variates.

A specific effort on stress bottom parametrization and its implementation in T-UGOm have been done: a new parametrization of stress, using the logarithmic velocity vertical profile parameterisation, has been established, and an original algorithm, which allows to prescribe geographical areas, has been developed. In addition to the improvement of the model bathymetry (using local charts digitalizations), this allows a more accurate simulation of the Amazon system. The preliminary simulations and sensitivity experiments will be presented.

FE approximations of shallow-water models

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Abstract

In the first part a constructive linear algebra approach is developed to characterize the kernels of the finite element discretized shallow water equations. Three kernel relations are identified as necessary conditions for the discretized system to share the same stationary properties as the continiuous sytem. The kernel concept is then used to characterize the smallest representable vortices. Both uniform and unstructured mesh situations are considered and compared. Issues such as decoupling of vortex modes are also examined. This study includes a number of classical finite element pairs and a variety of Raviart-Thomas and Brezzi-Douglas-Marini finite elements. In the second part a number of temporal procedures for solving the fast gravity and slow Rossby modes using the finite element method in space are presented and analysed. The analysis determines the stability of the schemes and the error in wave amplitude and phase that can be expected.

Application of an unstructured grid regional ocean model to the Solent-Southampton Water estuarine system.

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Abstract

The Solent-Southampton Water estuary is affected by an unusual tidal regime with the presence of the 'young flood stand' when sea level rise pauses at mid-flood and the 'double high water ' corresponding to an extended period of high water stand. A free-surface, primitive equation, unstructured grid model in terrain-following coordinates has been set up to reproduce water mass circulation in this estuary. A Mellor-Yamada level 2.5 turbulence closure scheme and wetting-drying scheme are included. The model is forced at river boundaries with daily river flows provided by the Environment Agency, at the ocean boundary with tidal harmonic constituents from the POL CS3 model and at the sea surface with wind data from a local meteorological station. Results from a short-term simulation have been compared with tide gauge data, salinity profiles and ADCP measurements collected in Spring 2001. An error assessment of the modelled tidal elevation using a tidal harmonic analysis indicates an error of less than 15 % in the amplitude and 10 degrees in the phase of the semi-diurnal tidal constituents M2, S2 and N2. The partially-mixed nature of the stratification in Southampton Water is accurately reproduced. Further works include the implementation of an ecosystem model to investigate the sensitivity of phytoplankton growth to physical forcings.

Discontinuous Galerkin Finite Element Method for Solving Two-Phase Flows

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Abstract

A finite element method is developed to solve the solutions of the incompressible Navier-Stokes equations for simulating two-phase flow. It uses the discontinuous finite element for the convective terms, a mixed finite element method for the viscous terms, and an explicit Runge-Kutta time integration for the time marching [1,2]. The incompressible Navier-Stokes equation is solved by the artificial compressibility method.[3] The numerical method is formally second-order accurate in space and time. A scalar transport equation is used to describe the motion of two-phase flows.[4,5] To capture the sharp interface boundaries slope modification is introduced.[6] Three test cases, broken dam problem, gas bubble rising in a viscous flow, and sloshing in an open tank, are demonstrated and validated. In the broken problem, the conservation of mass is validated and the profile of water front is well captured. The computational results show the capability on the shape interface capturing of the proposal finite element method.

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Unstructured mesh free surface ocean model using an arbitrary coordinate system

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Abstract

To apply Imperial College Ocean Model (ICOM) to global or regional ocean modelling, new methods have been developed for free surface flow simulation on a spherical or arbitrary shaped geodetic manifold in an arbitrary coordinate system. The finite element method is employed to solve the full 3-D Navier-Stokes equations and can thus resolve non-hydrostatic flows. The new implicit methods utilize free surface boundary kinematic condition and coupling the free surface with the momentum equations in a method akin to projection methods used to calculate pressure in incompressible flows. The methods are conservative and consistent with the discretised continuity equation. The implicit algorithm is not constrained by the CFL condition thus allowing the use of small elements or large time steps.

Several tests cases of global and regional ocean modelling and idealized water world have been conducted. To remove the pole singularity, a Cartesian coordinate system is used with its origin at the centre of the Earth. The computational domain is discretised with 3-D adaptive unstructured meshes. Super-parameteric element mapping is implemented to improve the accuracy of the representation of the curved free surface and bottom topography.

Using a wave equation approach in the 3D unstructured model T-UGOm

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Abstract

The Toulouse UGO model uses a 2D wave equation to solve the ocean external mode. The wave equation approach has the great advantage of being implicit, allowing for much larger time step than an explicit approach. In the wave equation approach, the 2D continuity equation is only weakly enforced.The main drawback of that is first that all conservative formulation are no more consistent (possibly such as momentum equation or tracer equation), and direct vertical velocity computation is no more suitable.

The author reviews the consistency and discretisation issues related to this problem, and presents the alternative schemes that are required. The numerical precision and computational costs of the new schemes are discussed. Additional comments on boundary conditions formulation and their consistency with the wave equation will be presented.

Internal Wave Modelling with ICOM

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Abstract

Internal gravity waves can provide a sufficient source of energy to activate strong diapycnal mixing near sloping bathymetry, which can in turn account for a significant portion of the overall oceanic vertical mixing. They can also be responsible for the transport of colder nutrient rich water up onto continental margins. We present two dimensional results of numerical investigations of internal wave interaction with idealised bathymetry using the Imperial College Ocean Model (ICOM), a non–hydrostatic, finite–element model that includes anisotropic mesh adaptivity. The ability of the model to focus resolution where it is most needed in response to the evolving flow makes ICOM an ideal tool to study the small–scale processes that result from the interaction of oceanic internal gravity waves with bathymetry. We also simulate small–amplitude vertical oscillations of a cylinder in a linearly stratified fluid which generates the famous "St. Andrew's Cross" wave–field.

A Storm in a Tea Cup: Self-induced Ekman Pumping in Columnar Vortices.

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Abstract

The flow past islands in shallow water is often seen to produce lee eddies. Due to the aspect ratio, this lee eddies are usually subject to the effects of bottom friction. This bottom friction produces an Ekman pumping scenario, in which the background rotation is replaced by the swirling of the eddy itself; exactly what occurs in a tea cup when you stir it with a spoon! However, previous model results of the idealised flow past islands show that the maximum vertical motion is located at the junction between the two eddies, whereas a purely Ekman pumping argument would place this maximum in the centre of each eddy.

The Imperial College Ocean Model is used to numerically simulate a columnar vortex confined to a cylindrical domain (the storm in the tea cup). This simulations are aimed at quantifying the vertical motion produced by self-induced Ekman pumping, with respect to the system parameters (Reynolds number, aspect ratio, etc). We consider both individual vortices and pairs of counter-rotating vortices in oblong domains. Motivated by the results from three-dimensional cylinder calculations, we seek to determine if a change in the position of the maximum vertical motion changes this relationship to the parameters. Our previous results show that the eddies that form behind an island are not closed off from exchanges with the free stream. We expect this to be key to the difference between the vertical motion in the case of a confined vortex.

Slip, the Indian Ocean Tsunami and GPS based tsunami warning systems

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Abstract

The Sumatra-Andaman Earthquake had a co-seismic moment magnitude of 9.1-9.3. The resulting tsunami caused colossal devastation and loss of life. Understanding the distribution and timing of slip in such massive earthquakes and their potential to generate a tsunami is invaluable to the safety of coastal inhabitants. Therefore in order to understand the influence of the rupture mechanism on the severity of the Indian Ocean Tsunami, we used co-seismic GPS data, together with campaign GPS, seismicity and or uplift data, to carry out an extensive analysis of co-seismic displacement and tsunami models. Here we present the results of five co-seismic slip inversions. From these results, vertical displacements of the Indian Ocean floor were derived and used to drive tsunami simulations using unstructured grid ocean models. Here we demonstrate how the GPS system in place in SE Asia, could have been used to produce a reliable forecast of the Indian Ocean tsunami, within about 30 minutes of the earthquake. We provide insight into the role played by the slip distribution and the timing of the rupture on the severity of the resulting tsunami. We conclude that the incorporation of permanent real-time GPS stations would represent a valuable component of future tsunami warning systems.

Impact of flux forcing in a North Atlantic configuration of the FEOM

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Abstract

A new prismatic version of a 3D Finite Element primitive-equation Ocean Model (FEOM) is used for the study of the North Atlantic (98^{o}W- 15^{o}E and 10^{o}S - 82^{o}N). The model was developed at the Alfred Wegener Institute for Polar and Marine Research (AWI), Germany. The Present version has a triangular unstructured horizontal mesh, refined in regions of steep topography with prismatic geopotential vertical levels compared to the older version using tetrahedral partitioning in the vertical. The model has a maximum finite element length of 30 km,mostly in deep ocean and a minimum of 2.5km in areas of steep topography and Labrador Sea area. Resolution in the vertical is fine near the surface and coarsens at depth. The sensitivity of the model with flux forcing will be presented using the ECMWF 40 year reanalysis flux data. The circulation, hydrography,heat transport of the model (focussing on the subpolar North Atlantic and the Labrador Sea) and a comparison with observati! on will also be presented.

The inverse finite-element ocean circulation model (IFEOM) and its sensitivity to control parameters

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Abstract

The inverse finite-element ocean model (IFEOM) estimates the ocean circulation by assimilating temperature and salinity data. It solves stationary equations for velocity and sea surface height (SSH), and treats the advective-diffusive tracer balances for temperature and salinity (T and S) as soft constraints.

IFEOM uses prismatic discretization of the model domain with non-conforming /continuous linear representation for the horizontal velocity field in horizontal /vertical directions, continuous linear representation for SSH, tracer fields and the potential of the vertical velocity. The latter is differentiated in z in order to get the vertical velocity.

IFEOM seeks for T and S fields which give minimum to its objective function. The latter penalizes residuals in the tracer equation, deviations of model variables from data available and also misfit between diagnosed deep velocities and that of the prognostic run of a prismatic version of FEOM.

The IFEOM is quasistationary and neglects the momentum advection. The absence of momentum advection is appropriate at coarse resolution everywhere except for the equatorial belt. The equatorial belt introduces a major difficulty for IFEOM and requires a careful selection of weights and auxiliary constraints. The missing momentum advection is treated as an additional control field which is penalized to the mean momentum advection term of the prognostic run in some vicinity of the equator.

The structure and basic principles of IFEOM, the influence of the control parameters on the circulation pattern and the results of application of IFEOM to the reconstruction of the pentadal variability of the circulation in the North Atlantic (the mesh covers the area from 20 S to 80 N) are presented.

Global Unstructured Grid Ocean Modeling

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Abstract

We discuss the application of unstructured grid-based numerical methods to the simulation of global oceanic flows. Some aspects of these techniques are particularly advantageous in the global context, such as the capacity to refine resolution in local regions of interest. However, various technical challenges need to be overcome if unstructured grid models are to be competitive in performance and accuracy with traditional Cartesian grid-based analogues.

Our efforts up until recently have focused upon the development of a numerical modeling framework, along with the derivation and application of Arakawa C-grid based finite volume methods. The modeling framework is a versatile, graphical software system for problem-setup, mesh generation and adjustment, and data manipulation. This structure is now largely functional, and we have been using it to perform numerical tests, as well as realistic, challenging physics simulations: i.e., climate-driven ocean simulations, and barotropic and baroclinic tidal simulations.

Our C-grid based methods have excellent robustness and conservation properties, and resolve accurate barotropic tides, as well as the rudimentary structure of the global baroclinic ocean circulation. However, phenomena that depend upon very accurate representations of baroclinic dynamics are poorly resolved, and numerical artifacts are detectable. The Gulf Stream is too weak, and a coherent thermohaline circulation does not appear. Although at first suspected to be a problem of parameterization, it now appears that these deficiencies may be due to inaccuracies in the basic baroclinic discretization. When we reproduce previous simulations of the generation of baroclinic waves by the global barotropic tide, waves are generated in the right general regions, but have very exaggerated phase speeds, and quickly contaminate solutions with numerical noise.

The challenge now is to improve model accuracy without having to go to unreasonably high resolution. We are working on the development of higher accuracy methods, and hope to make comparisons with spherical analogues of other techniques that have appeared in the literature. The existence of a versatile modeling framework makes it relatively painless to interchange basic numerical methods while analyzing the same complex problem. The latest results and discussion pertaining to all of these issues will be presented at the workshop.

Local mass and energy conservation in spectral-element discretizations of the sphere (& torus)

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Abstract

The spectral element method (SEM) uses a global weak formulation; therefore for several equation types (Burgers, shallow water, Navier-Stokes etc.) exact semi-discrete mass and energy conservation can be obtained, including when one writes the equations in primitive instead of conservation form. For cubic quantities such as shallow-water energy, conservation is semi-discrete, meaning exact assuming exact time integration. For linear and quadratic invariants such as mass and kinetic energy, the discrete approximation to the conserved quantity is conserved exactly. Furthermore, the conservation is local, meaning that one can show that the change in the conserved quantity in an element is given by the sum of the fluxes around the perimeter of the element. This conservation is a consequence of the fact that, even on non-orthogonal unstructured meshes, the discrete divergence operator is the adjoint of the discrete gradient operator. Global conservation is then a consequence of the fact that the flux terms between two adjacent elements exactly cancel. The advection scheme remains oscillatory, but the oscillations are localized and thus much reduced when compared to global spectral methods.

Finite-element sea ice and ocean modeling at AWI

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A. Huerta-Casas, Silvia Massmann, J. Schröter, D. Sidorenko,
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Abstract

Finite-element ocean circulation model coupled with ice model is used in a number of projects carried out at AWI. We present several studies done with the model which include ice and freshwater formation modeling in the Southern Ocean, study of bottom-pressure fluctuations in the Atlantic sector of ACC, ice modeling and ice velocity assimilation in the Arctic. We also give a brief overview of our current activities, including tidal modeling and and regional and global setups of FEOM.

A FE coastal ocean model: Improvements to Semi-Lagrangian, Coriolis, and other approximations.

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Abstract

The coastal ocean with its highly irregular shorelines and topography provides a natural place to apply unstructured grid methods. An objective of this work is to develop a robust and efficient numerical model that can be used for large-scale high-resolution simulations of coastal ocean dynamics. The model RiCOM (River and Coastal Ocean Model) is a multipurpose 3D primitive equation hydrodynamic model that uses a semi-implicit time approximation, uses a semi-Lagrangian advection scheme, and uses a finite element spatial discretization that is based on the RT0 triangular and quadrilateral elements. There are several recent developments that may be of interest to others.

Semi-Lagrange methods: Several new and old methods for calculating trajectories and interpolating at the foot of the trajectory were developed and compared. A power series in time for calculating trajectories was found to offer the best combination of accuracy and efficiency. The method can be applied to elements with constant spatial gradient in velocity such as triangles with linear bases, the RT0 elements, and the P1nc-P1 element. A quadratic interpolation method for unstructured grids was developed and is more accurate than a variety of linear methods.

Coriolis: Rather than use reconstruction methods to derive the tangential velocity on an element edge for use in the Coriolis discretization, a direct finite element approximation (as suggested by E. Hanert) is more straightforward and consistent with the rest of the equations. The problem of a Kelvin wave propagating in a circular basin (from D. Ham) was used for testing.

Field tests: A detailed comparison between RiCOM, Tide2d (a harmonic in time FE model), and a set of observations is being made for Cook Strait, New Zealand. The current tests with a diagnostic density will be expanded to a full baroclinic calculation.

Forecasts: The model is now embedded into a forecasting system in New Zealand that is linked with the UK Met Office and includes a Local Area Weather Model (NZLAM), the model for ssh (RiCOM), and a wave model.

The prismatic Finite Element Ocean Model

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Abstract

The finite-element ocean circulation model (FEOM) of AWI has been successfully used in applications to the North Atlantic, the Southern Ocean (with finite-element ice model) and on the global scale. We present a modified version of the model based on prismatic spatial discretization and $P_1 - P_1$ basis functions. The dynamical equations are solved with the Characteristic Galerkin based split (CBS) method, which provides stabilization for both advection and pressure modes. The Taylor–Galerkin (or Characteristic Galerkin) method and its flux-corrected transport (FCT) variant are implemented to solve the tracer equations. Other features, including the support for different vertical discretization, the algorithm for reducing pressure gradient errors, rotated diffusivity and viscosity and Gent-McWilliams parameterization, and biharmonic viscosity, are added in the current model. We discuss implementation of these features and present a set of tests of their performance. In particular, we compare performance of advection schemes available in FEOM, biharmonic vs. Laplacian viscosity, the impact of orientation of diffusion on overflows, and also give comparison of P_1 representation of velocities in the standard FEOM with its P_1^{NC} counterpart which clearly illustrates the effect of stabilization and sets bounds on stabilization parameter.

Unstructured Finite Volume Modelling for the Atmosphere

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Abstract

There is still much scope for improvement in numerical algorithms for adaptive modelling of the atmosphere. If they are to compete with the non-adaptive techniques used operationally, adaptive schemes may need to have all of the properties of conservation of mass, momentum and some higher moments, high order accuracy, accurate wave dispersion and efficiency.

We present solutions of the shallow water equations solved using OpenFOAM. This finite volume library uses arbitrarily unstructured meshes (cells can take any three dimensional shape). The order of accuracy is >=2, local conservation is exact, wave dispersion is as accurate as a structured staggered mesh and the implicity solution means that the flow Courant number can be greater than one. We will describe how some of this has bean achieved and then present results comparing different mesh structures.

Without higher order accuracy, scale interactions between regions of mesh with different resolution cannot be captured. Without the accurate wave dispersion, grid scale forcing and sharp mesh refinement patterns lead to spurious grid scale waves.

Application of the Imperial College Ocean Model (ICOM) to simulate tidal dynamics in present day and geologically ancient seas and oceans

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Abstract

We apply the Imperial College Ocean Model (ICOM) to the study of tidal dynamics in geologically ancient seas and oceans. The model is first validated using a selection of present day seas and the global ocean. This represents one of the first applications of ICOM within 'realistic geometries'.

Our work makes use of several novel techniques. Firstly an unstructured mesh, constructed to optimally represent bathymetry (i.e. resolution is focused in areas of rapidly changing bathymetry) is used. Secondly, the equations are solved in Cartesian space, mapped to a sphere with an origin at the centre of the Earth.

ICOM's tidal capability is tested using the global ocean, the North Atlantic Ocean, the Mediterranean Sea, the North Sea and the Baltic Sea. All have different challenges, ranging from modelling a purely astronomical tide (the global ocean and Atlantic Ocean), to a purely boundary-driven tide (the North Sea), to a combination of both (the Mediterranean Sea and Baltic Sea). Comparison is made against a selection of well-known global ocean tide models and tide gauge data where available. The results are very encouraging, especially since ICOM does not assimilate any tide gauge or satellite altimetry data.

Interest in geologically ancient seas stems from a lack of modern analogues to the vast (e.g. 5-10x106 km2, whereas the present day North Sea is 0.75x106 km2) epi-continental or epeiric seas of the past. We present results of global and regional models from the Pennsylvanian (Late Carboniferous, c. 300 Ma) and Lower Cretaceous (c. 115 Ma). Such modelling has aided our understanding of tidal dynamics in ancient epi-continental seas and the sedimentary deposits laid down in them.

Aspects of spatial discretization on unstructured staggered grids

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Abstract

Use of a staggered location of the variables in a finite difference / finite volume setting is a good way to avoid spurious modes in the surface elevation. These occur when a colocated positioning of the variables is used. Because the spatial discretization on a Cartesian structured grid using a staggered positioning of the variables is no harder than using a colocated positioning, many structured grid codes (e.g., Delft3D, Mike) employ a staggered grid.

However, extension of a staggered structured grid discretization to an unstructured grid is not straightforward. A possible extension is presented in [1]. Though originally developed for application to the Euler and Navier-Stokes equations of gas dynamics, this method can equally well - with minor algorithmic modifications - be applied to coastal applications.

In the presentation, the focus will be on the following issues:

- location of the unknowns
- discretization of the advection term, including extension to higher order
- discretization of the surface elevation gradient term
- reconstruction of the velocity field

[1] I. Wenneker, A. Segal and P. Wesseling. A Mach-uniform unstructured staggered grid method. Int. J. Num. Meth. Fluids 2002; 40:1209-1235.

On The Scaling Properties of Tetrahedral Supermeshes

Luke J West

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Abstract

Conservative interpolation between arbitrary meshes is possible using an intermediate supermesh, but the construction of a useful supermesh is fraught with difficulties.

A successful implementation of a general algorithm is presented.

Interpolating between grids is a common task, but simple methods are non-conservative in general, and therefore unsuitable for many applications.

For example, in an adaptive framework where regridding occurs frequently, it is difficult to collect quality temporal statistics using non-conservative methods.

Another example is coupled climate modelling in which surface fluxes between oceanic and atmospheric components must be conserved even if their respective surface grids are mutually arbitrary.

Results for 2D and 3D meshes are presented and the scaling properties of their resultant supermeshes are investigated.

Multiple Material Modelling on Unstructured Meshes

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Abstract

The numerical simulation of multiple immiscible materials is of interest in many fields of scientific research. Many of these, such as marine wave breaking, require the ability to cope with large deformations therefore restricting the use of Lagrangian mesh movement. In an arbitrarily Lagrangian Eulerian framework explicit representation of the interface, using marker particles or surfaces, is possible; however, processes such as mixing require special treatment and render conservation problematic. In the alternative volume of fluid method each material is represented by a volume fraction, which is found using a finite volume discretisation of the linear transport equation. This method is capable of dealing with arbitrary levels of deformation and ensures mass conservation; however, with most low-order advection schemes it suffers from a tendency to smear the material boundary. To prevent this the volume fraction is often used to construct an interface allowing the exact flux across a cell face to be calculated. This process maintains a sharp interface and therefore minimises nonphysical mixed cells. However typical multidimensional extensions to this process depend on either operator splitting or predictor-corrector steps to ensure physical volume fractions, processes which are either impossible or complex on unstructured meshes. Additionally the interface reconstruction process is particularly difficult to generalise to multidimensions and arbitrary meshes. Flux limiters offer an alternative method to ensure satisfaction of the total variation diminishing principle without interface reconstruction. They can also be easily generalised to multidimensions but have been rejected in the past due to their poor shape preserving qualities. Here we present some results of our control volume finite element implementation of the Hyper-C flux limiter on an unstructured mesh. Through its connectivity this method circumvents the need for corner coupling and improves the scheme's shape preserving abilities. These results have been verified against experimentation and are currently being tested for use in coastal engineering and high velocity impact.

Use of unstructured grids in nearshore wind wave model SWAN

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Abstract

SWAN (Simulating WAves Nearshore) is a third−generation spectral wave model that calculate spectra of random short−crested, wind−generated waves in offshore and coastal regions (http://vlm089.citg.tudelft.nl/swan/index.htm). The kinematic behaviour of the waves is described with the linear theory for surface gravity waves whereas the wave dynamics are associated with the processes of generation, dissipation and nonlinear wave−wave interactions. In SWAN, they are represented with the state−of−the−art formulations.

Since, the characteristic spatial scales of the wind waves propagating from deep to shallow waters are very diverse, a flexible grid would be required to allow local refinement of the mesh near the coast without incurring overhead associated with grid adaptation at some distance offshore. Traditionally, this can be achieved by employing a nesting approach. The use of unstructured grids, however, offers a good alternative to nested models not only because of the ease of local grid adaptation but also the relatively short time and the associated modest effort to generate grids about complicated geometries. Moreover, this can be automated to a large extent. This motivate us to implement a numerical algorithm in SWAN appropriate to wind waves computations on unstructured grids. Currently, we restrict ourselves to triangular meshes, although this is not a fundamental restriction; other type of meshes can be used as well, e.g. hybrid grids.

Contrary to the most third−generation spectral wave models, the numerical propagation scheme in SWAN is unconditionally stable i.e., it is not subjected to a CFL stability criterion. It made use of the four−direction (symmetric) Gauss−Seidel iteration technique. This method appears to be very effective on regular meshes. Furthermore, it is also very robust in practical shallow coastal applications since, the permitted grid resolution and time steps are mutually independent.

Because of these nice properties, this solution technique is tailored to unstructured grids. A vertex−based algorithm is employed in which the variables are stored at the vertices of the mesh and the wave balance equation is solved in each vertex assuming a constant spectral grid resolution in all vertices. Next, an ordering of vertices is established in such a way that sweeping through each vertex can

be made by using the updated information from the surrounding vertices as soon as it is available. The two upwave faces connecting the vertex to be updated with its two updated neighbours encloses those wave energy propagation directions that can be processed in the spectral space without having stability problems. After updating all vertices, the process continues by sweeping through the vertices in a reverse manner, allowing waves to propagate from other directions. This is repeated until all vertices are updated in the sense that wave energy from all directions has been transmitted through geographical space. This technique is very effective, requiring only a few passes through the grid.

A number of test cases have been conducted for the verification of the present numerical method. Aspects as numerical accuracy and performance are considered. The approach and the obtained results will be highlighted in this talk.

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